Hydrodynamics modeling of the dynamics of Sn droplet target for the EUV source

Akira Sasaki

Japan Atomic Energy Agency

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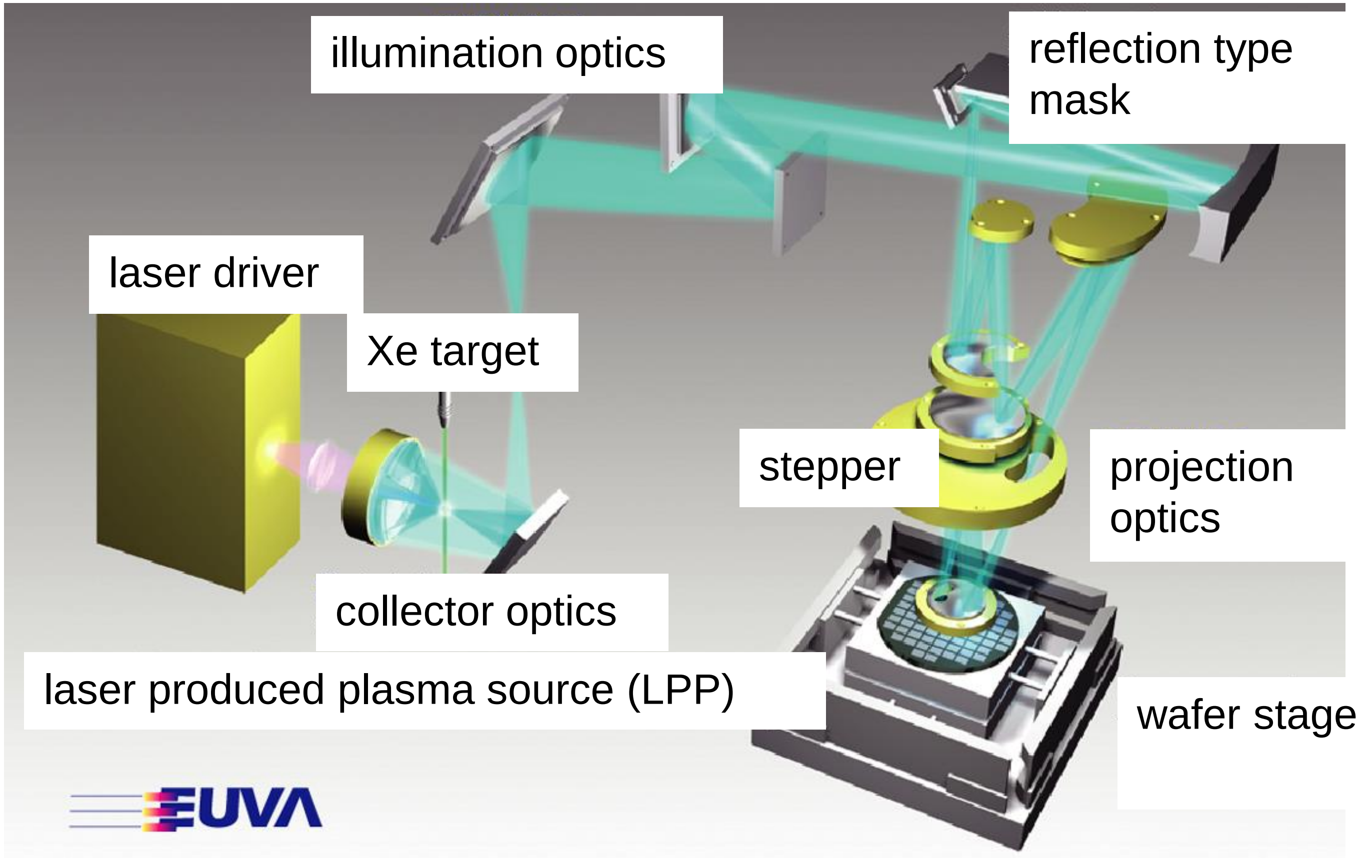
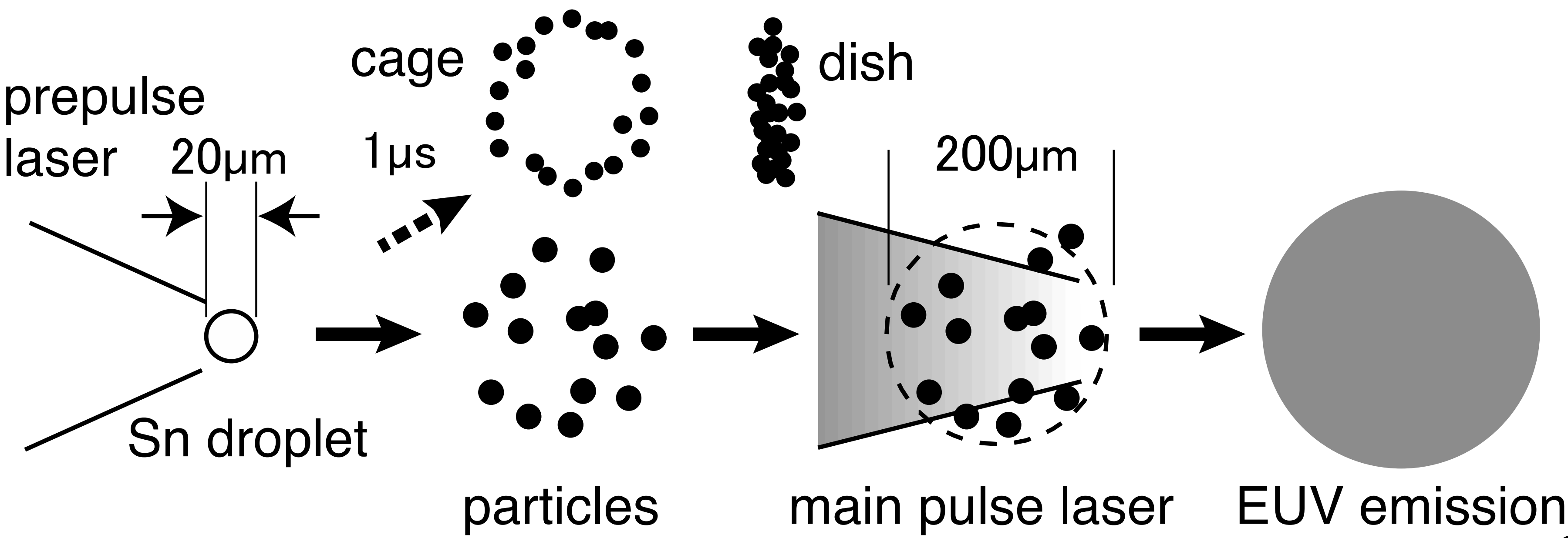
Introduction

- For sophisticated pumping scheme of EUV sources, optimization based on improved modeling of laser and target interaction is required.



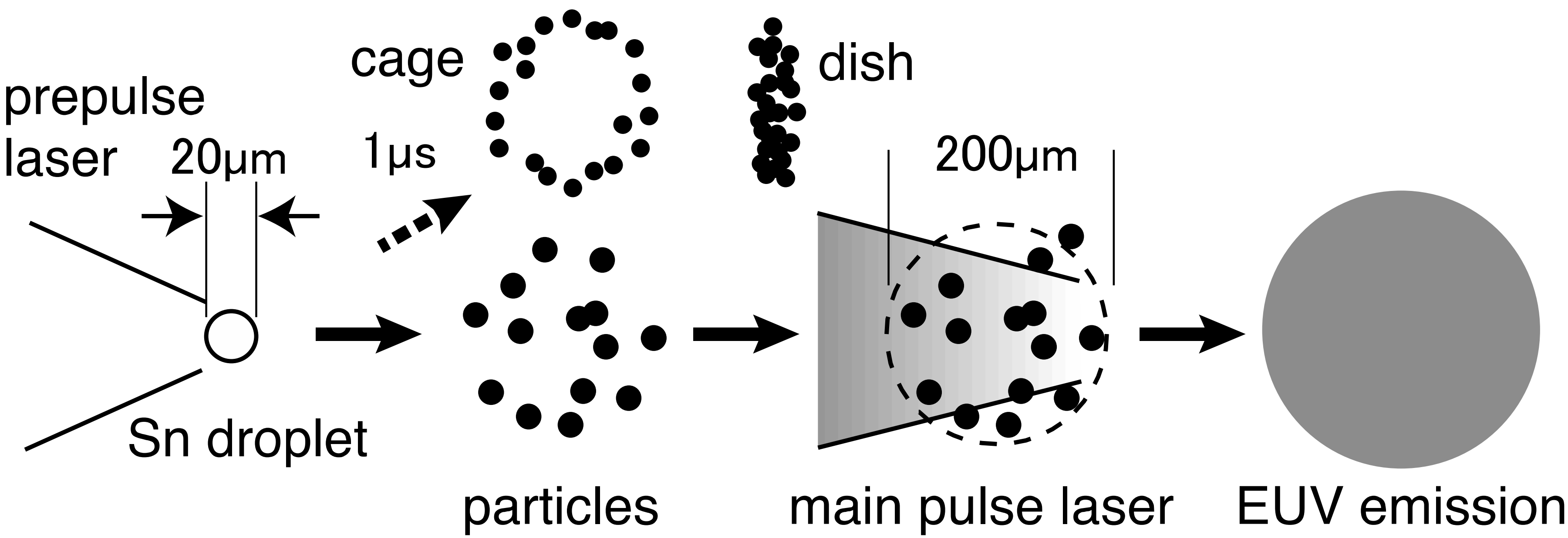
Updated scenario of pumping EUV source

- Target is broken up into particles by prepulse irradiation.
- Particles remains until main pulse irradiation. Main pulse laser interacts with particles to produce uniform, low density plasmas.
- Distribution of particles depends on laser condition.

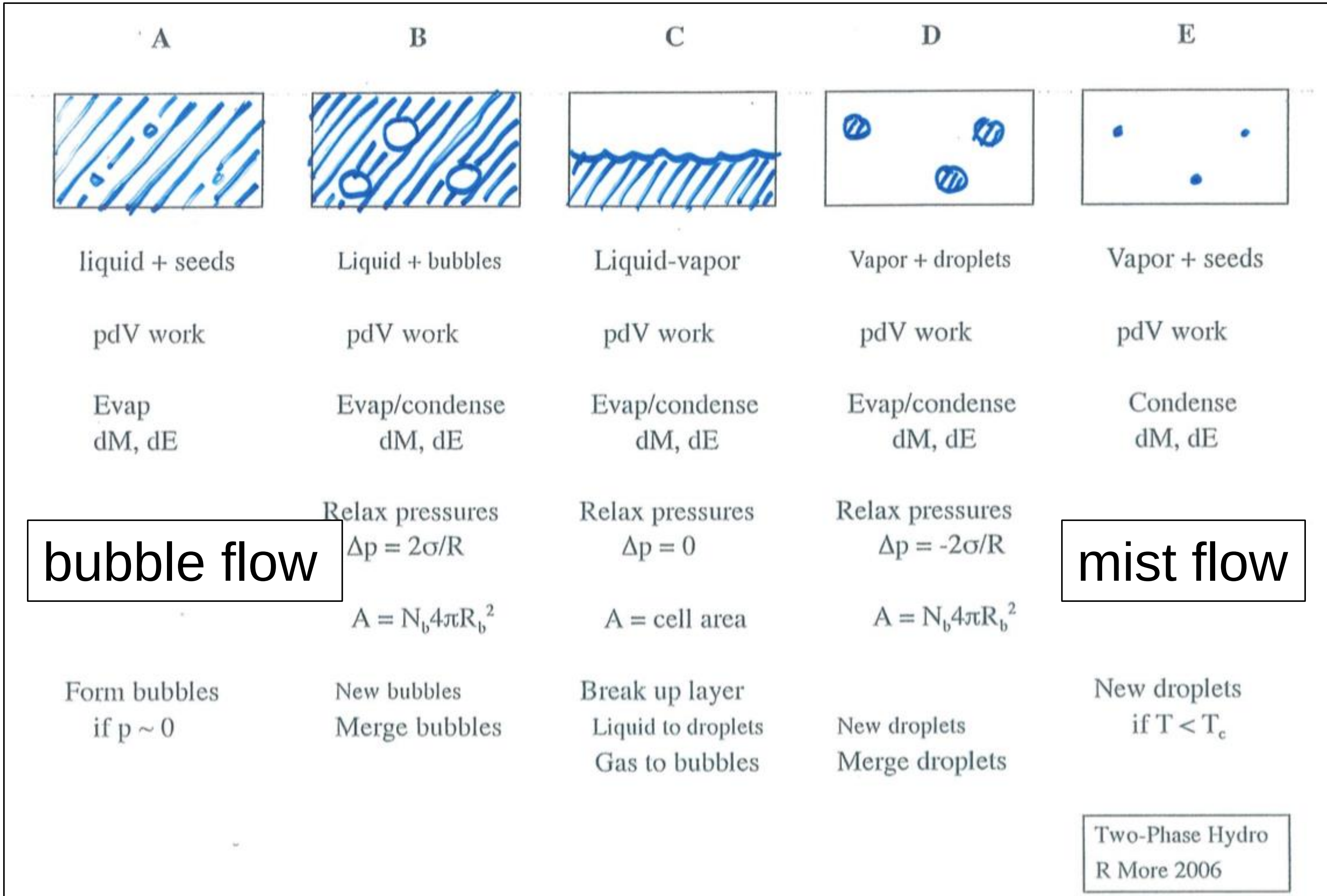


Requirements to modeling of the EUV source

- Hydrodynamics model of the target fragmentation and particle emission should be developed.
- Interaction between laser and particles, transport in plasmas in the presence of particles should be investigated.



Situation of modeling



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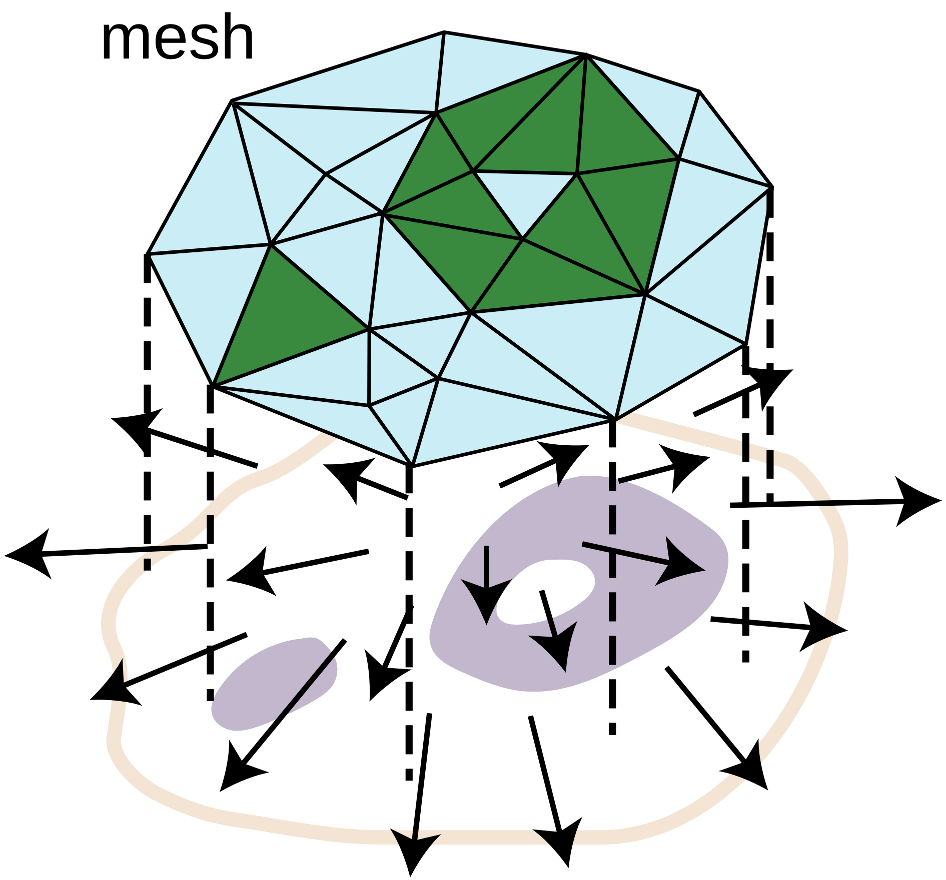
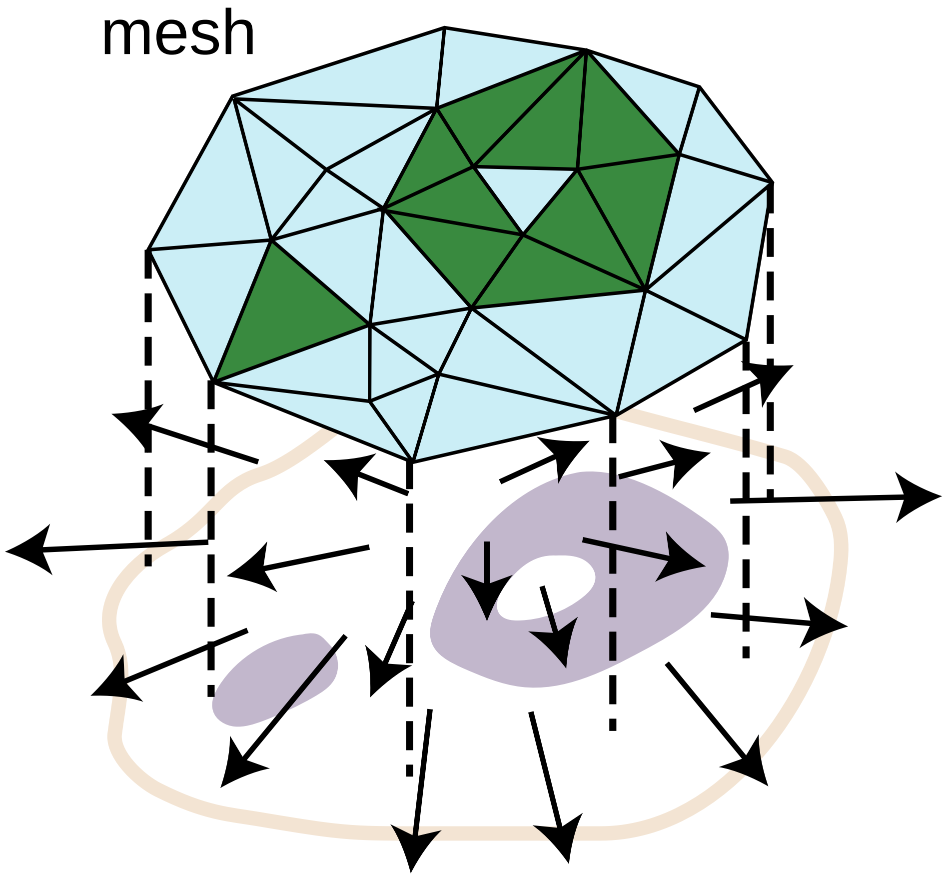
Application of Lagrangian hydrodynamics



- Modeling of bubbles and clusters as well as their flow have difficulties using both fluid and particle approaches.
- Modeling of phase transition should be easier on the coordinates moves along the fluid (Lagrangian mesh).

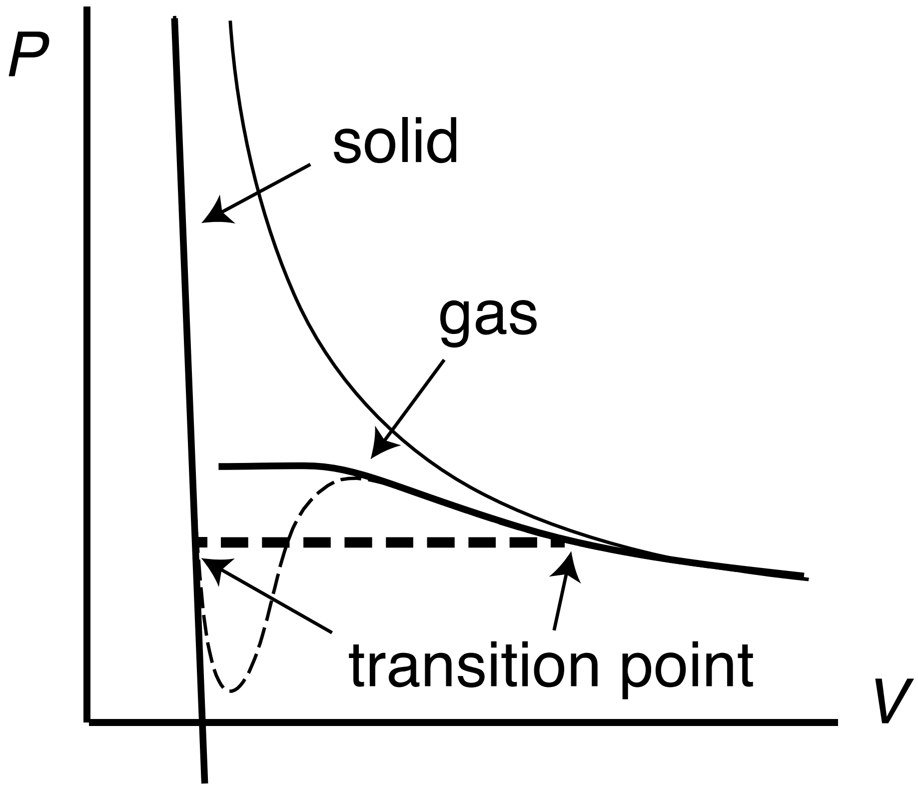
Advantage of using Lagrangian mesh



- We develop novel rezoning algorithms to represent bubbles and clusters by Lagrangian mesh for which theory of phase transition is applied.
- Property of the material (gas/solid) as well as surface tension can be defined for each cell.

Modeling of phase transition

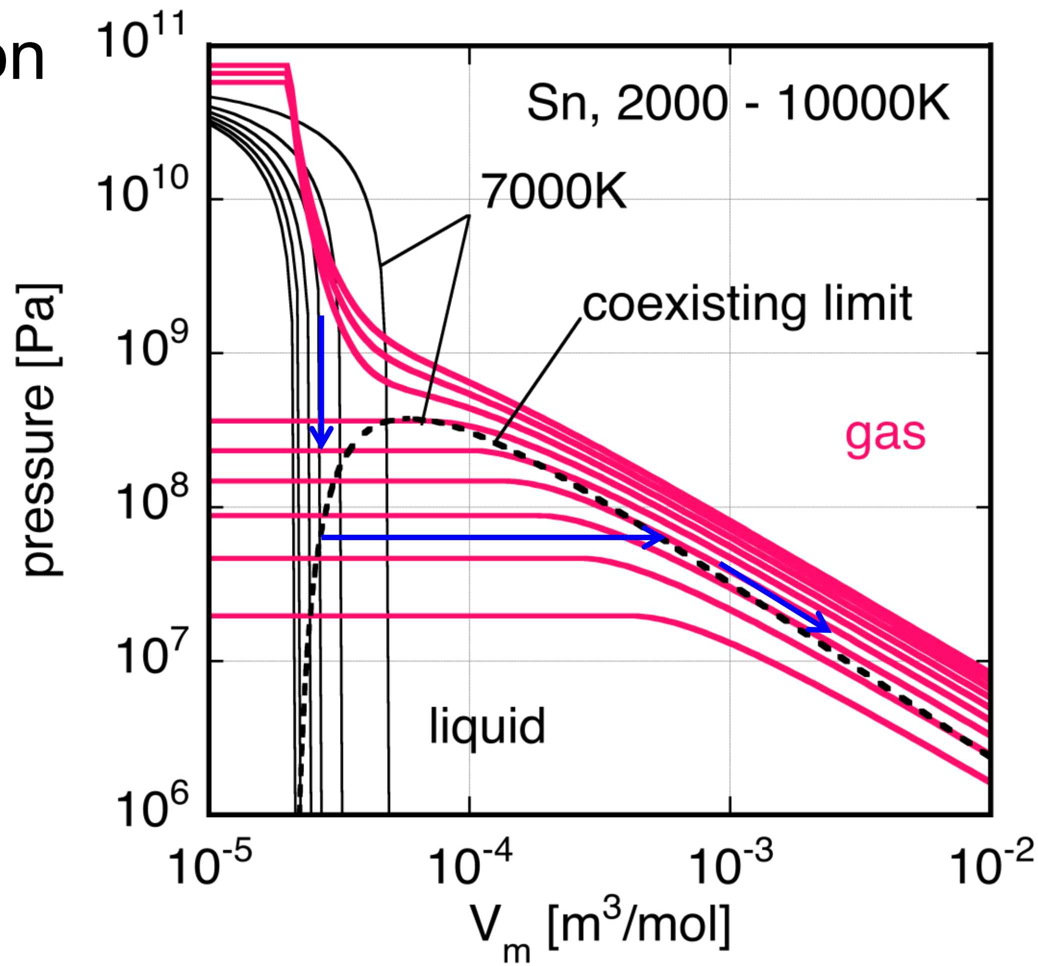
- We use simple Van-der-Waals model to determine the condition of phase transition and transition point.



- Instead of averaged phase of gas and solid used in previous models, mixed phase is determined explicitly by an arrangement of solid and gas phase.

Equation of state of Sn

- The density of transition point is determined using Van-der-Waals model.
- Ideal gas and solid phase are taken into account to calculate internal energy and entropy.



- Pressure at the transition point is considered as the equilibrium pressure of solid phase.

Equations of hydrodynamics of ideal solid

$$DP = - b_m \frac{DV}{V}$$

- Positive or negative pressure acts against compression or extension.

$$H = b_m \frac{DV^2}{2V}$$

- Internal energy are stored as thermal energy and energy for strain.

$$C_v = 3R$$

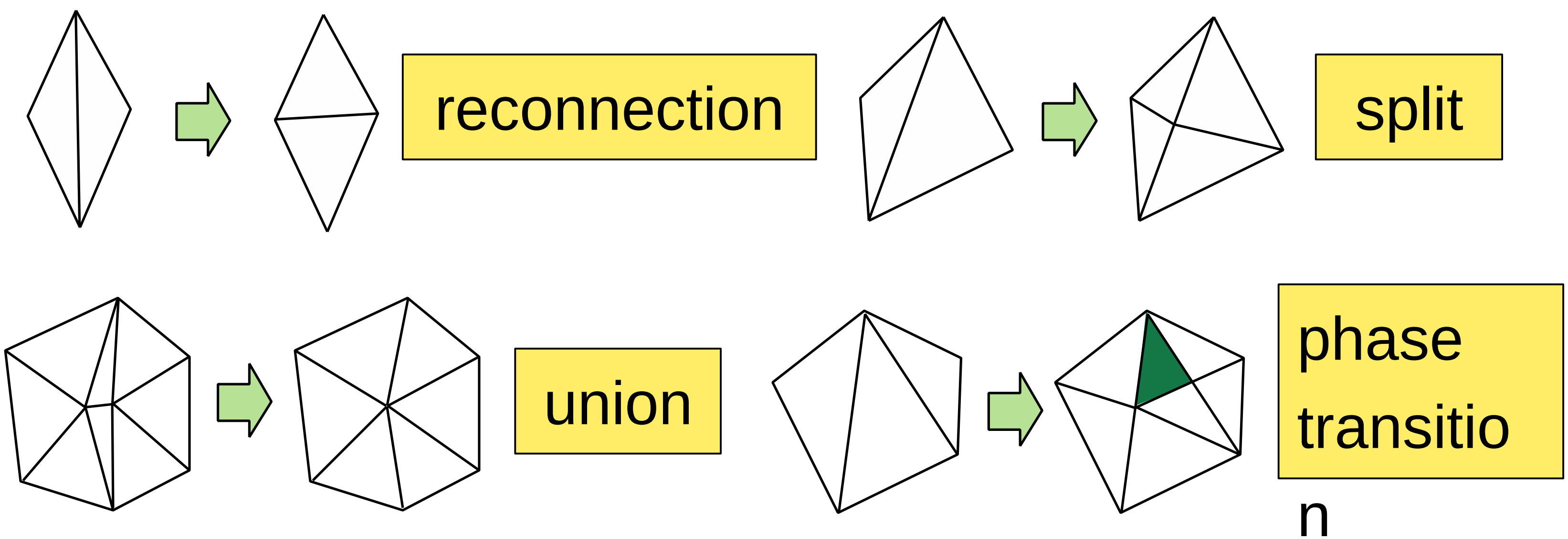
- Thermal energy is determined by Dulong-Petit law.

$$C_V \frac{dT}{dt} + P \frac{dV}{dt} = X \qquad U(t) + H(t) + PDV = U\left(t + Dt\right) + H\left(t + Dt\right)$$

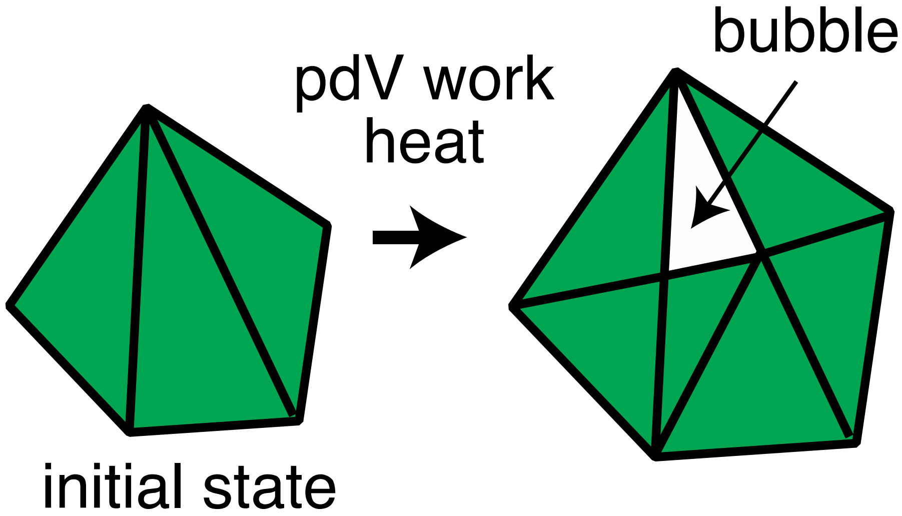
- Temperature is determined to initial thermal and strain energy and work done, to be equal to final thermal and strain energy.

Rezoning algorithms

- Rezoning algorithms are originally developed to avoid mesh collapse, and used to represent bubbles and clusters.
- The algorithms are also applied to phase transition by dividing a cell to form a group of cells to have correct ratio between gas and solid.



Phase transition model



- If condition of phase transition is satisfied, the cell is split into gas and solid cells.

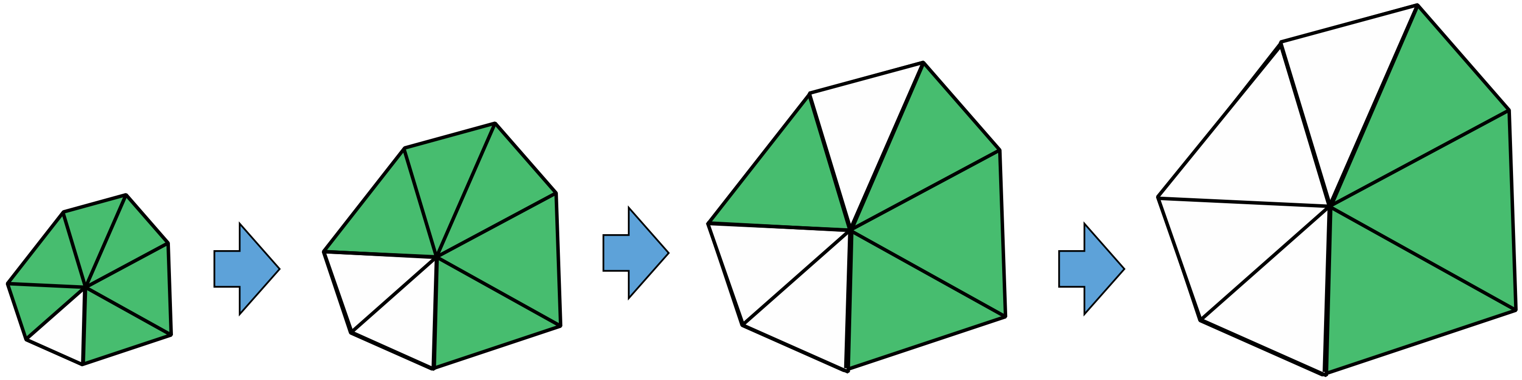
$$V = xV_L + (1 - x)V_G$$

$$U_i + H_i + F_i = U_o + F_o$$

- Volume and sum of thermal, strain, and surface energy are conserved for the group of the cells before and after transition.
- Bubbling, condensation, and mechanical fracturing are taken into account using only one procedure.

Model of evaporation and condensation

- Bubbles and clusters will grow gradually during evaporation and condensation.
- A super cell is defined from a group of cells, which share the same point, and redistribute mass and internal energy to maintain correct solid gas ratio.
- Number of gas (solid) cells in a meta-cell is increased as the evaporation (condensation) proceeds.



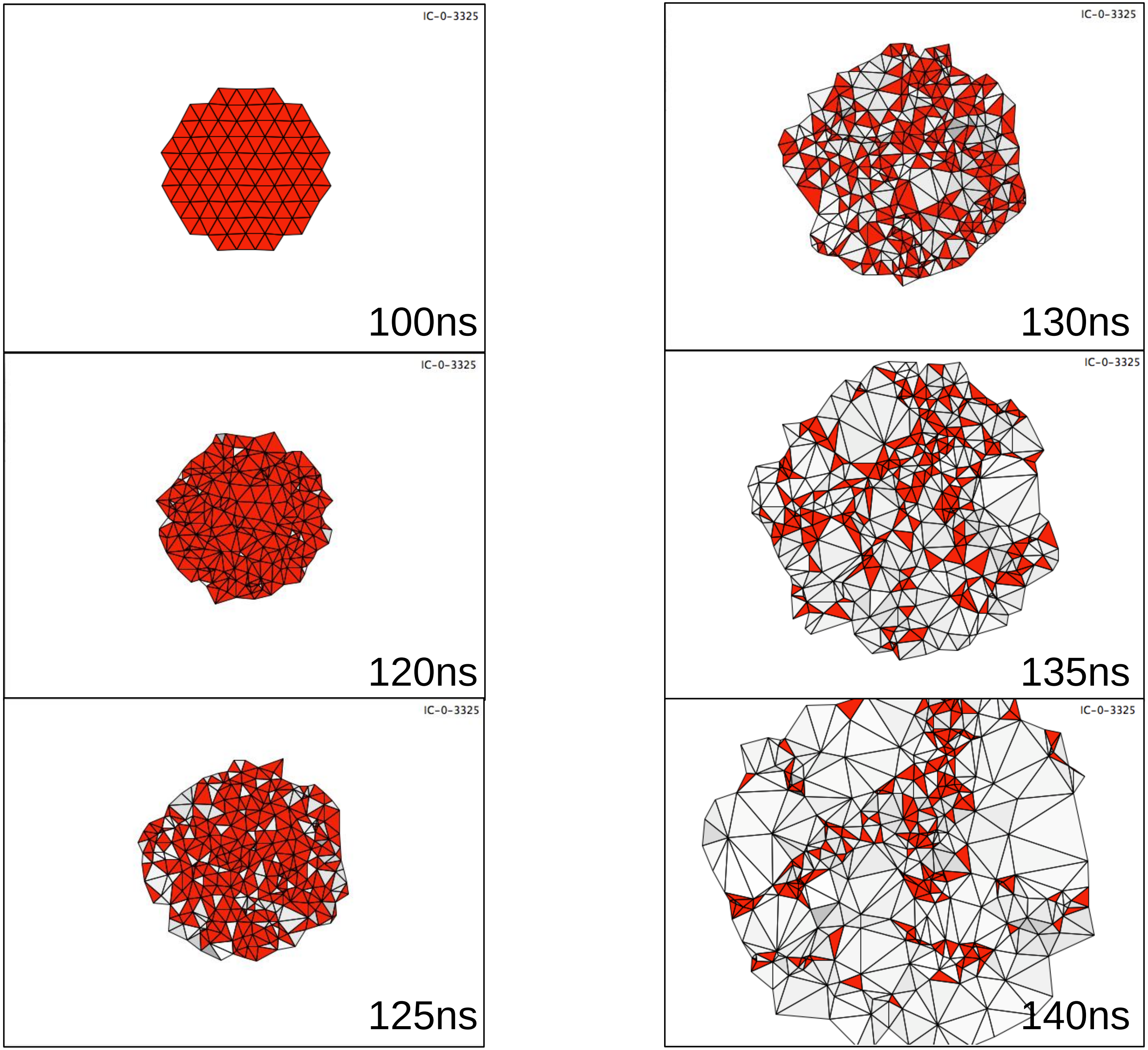
Test case

- Boiling hot Sn cylinder.

  $T_{initial}$= 4000K, density= 4800 kg/m^3, r=10μm

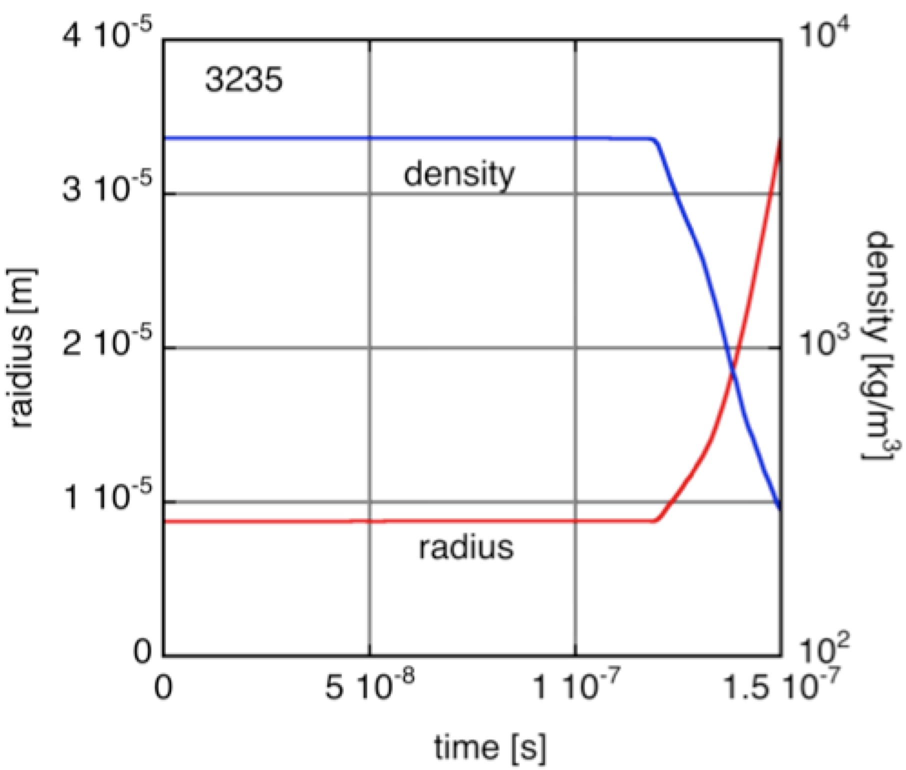
  2 dimensional, cylindrical geometry

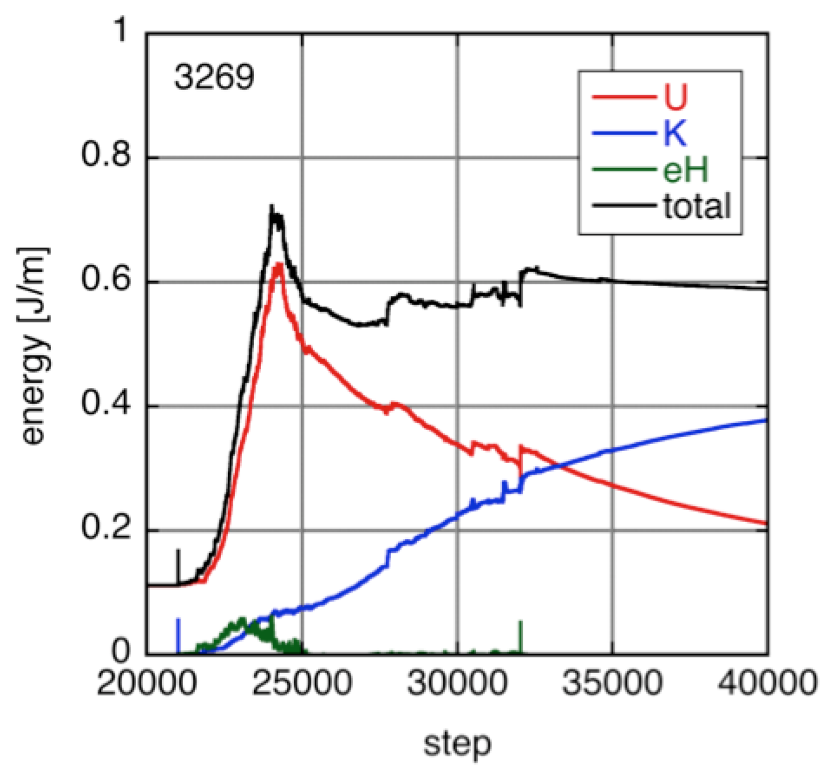
  no latent heat, no surface tension


IC-0-3325
100ns
IC-0-3325
130ns
IC-0-3325
120ns
IC-0-3325
135ns
IC-0-3325
125ns
IC-0-3325
140ns

Preliminary results

- Initially, liquid expands slowly, and after delay time, bubbles appear to drive rapid explosion.
- Latent heat should be taken into account to improve energy conservation.





Modeling of latent heat

- Temperature after transition is determined to conserve the Gibbs free energy, which is calculated from internal energy, energy of strain, and entropy.

$$G = U + H - TS$$

gas $$S_{gas} = Nk_B \ln\left(\frac{V}{N}\right) + \frac{3}{2}Nk_B\left(\frac{5}{3} + \ln\left(\frac{2\pi m k_B T}{h^2}\right)\right)$$

solid $$S_{solid} = Nk_B\left(1 - \ln\left(\frac{\hbar\omega}{k_B T}\right)\right)$$

Summary

- Rezoning algorithms, which is useful for 2D Lagrangian hydrodynamics simulation, have been developed.
- Theoretical model of hydrodynamics of mixture of gas and solid, as well as phase transition has been developed.
- Test calculation is carried out.
- Model of latent heat and surface tension is investigated.
- Laser absorption and transport in the preformed plasmas in the presence of clusters should be investigated.